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Sediment Magnetic Proxies Reflect Post-Glacial Climate Change for East-Central New Hampshire

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SEDIMENT MAGNETIC PROXIES REFLECT POST-GLACIAL CLIMATE CHANGE FOR EAST-CENTRAL NEW HAMPSHIRE

BY

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Table of Contents

Tables

List of Figures

Abstract

The magnetic properties of Pea Porridge Pond, NH were analyzed in an attempt to reconstruct Holocene climate change. Magnetic measurements include magnetic susceptibility (χ), anhysteretic remanent magnetization (ARM), isothermal remanent magnetization (IRM), saturation isothermal remanent magnetization (SIRM), coercivity distributions of IRM, and hysteresis loops. ARM/IRM and S-ratios were calculated, and a Day (Day et al., 1977) plot was created using data from the hysteresis loops. The sediment magnetic record is divided into six zones. High concentration-dependent parameters in Zone 1 (prior to 14 ka) suggest an initial unstable landscape in which erosion contributed to the input of magnetic minerals. Zone 1 is dominated by clastic, sedimentary input and detrital magnetic minerals are coarse-grained. The overall sediment magnetic properties are dominated by low-coercivity minerals. Zone 2 (14.0-13.6 ka) is characterized by an increase in organic matter and a decrease in the concentration of magnetic minerals. A warmer climate stimulates lake productivity and causes anoxic conditions in the sediment, resulting in decreasing concentration-dependent parameters. The minerals are still coarse-grained and of low-coercivity. Sediments deposited during Zone 3 (13.6 -10.0 ka) are likely affected by the processes of dilution and dissolution and show a dramatic decrease in concentration-dependent parameters (χ, ARM, IRM). The spruce maximum (~11.0 ka) occurs during this zone and may lead to the acidification of soil and the dissolution of Fe-minerals. Narrow coercivity distributions from this zone indicate the production of biogenic magnetite likely stimulated from the addition of dissolved Fe. Zone 4 (10.5-8.5 ka) shows a transition from paramagnetic clays to diamagnetic, organic matter. Zone 5 (8.5-3.0 ka) shows little change in sedimentary input but magnetic properties indicate a high-coercivity component and samples are almost entirely diamagnetic. Zone 6 (<3.0 ka) indicates an increase in detrital sedimentary input, likely occurring because of erosion due to anthropogenic activities. A decreasing sediment accumulation rate from Zone 1 until Zone 5 indicates a dry climate, and increasing sediment accumulation throughout Zones 5 and 6 suggest a moister climate.

Introduction

In recent years, a growing interest in both climate change and the likely effects of human activities on global warming has demonstrated a need for accurate reconstructions of past climatic conditions. Paleoclimatic reconstructions allow for the estimation of natural climate variability as well as the rates of climate change (e.g. Geiss et al., 2003, Shuman et al., 2004). These estimations can then be used to further refine and improve existing climate models.

Sediment magnetic records have become a useful proxy for reconstructing the paleoclimatic history of a given area and can provide an alternate method of reconstruction that may capture environmental change from a different perspective. They can also aid in improving the robustness of reconstructions. The magnetic properties of various environmental samples, such as those of lake sediments, can be measured both quickly and inexpensively. Unlike some geochemical and/or biological approaches, the magnetic measurements are not destructive and allow for a variety of different measurements to take place. Also, the magnetic record persists during even the coldest of climates, whereas some biological indicators may not (Williams et al., 1996).

Sediment magnetic studies attempt to characterize the magnetic components of a given sample in terms of its concentration, mineralogy, and grain-size distribution. These characteristics can vary with changes in climate, and can provide information on the likely environment during a particular time period. However, the sediment magnetic record alone cannot be used to reconstruct past climate. Often, the influence of climate change on sediment magnetic properties is indirect and demonstrated through comparison with other proxies such as pollen records. These comparisons are necessary as other factors can influence the flux of magnetic minerals in a lake. For example, mechanical and chemical weathering processes can affect the amounts, types, sizes, and availability of iron oxides (Rosenbaum et al., 1996).

In this study, I use magnetic parameters to carefully construct the sediment magnetic record for Pea Porridge Pond in east-central New Hampshire to show the response of sediment magnetic properties to changes in the paleoenvironment and, further, changes in paleoclimate.

Methods

Site Description

Pea Porridge Pond is a 48-ha freshwater, oligotrophic lake lying in a broad depression at 197-m elevation (43.941 N, 71.188 W) in east-central New Hampshire. It lies within the extent of the last glaciation and is therefore expected to reflect ice-proximal conditions during deglaciation as well as post-glacial lake evolution. Mean annual rainfall for the region is 1185.4 mm (WorldClimate, 2011) The watershed is forested but shows signs of development.

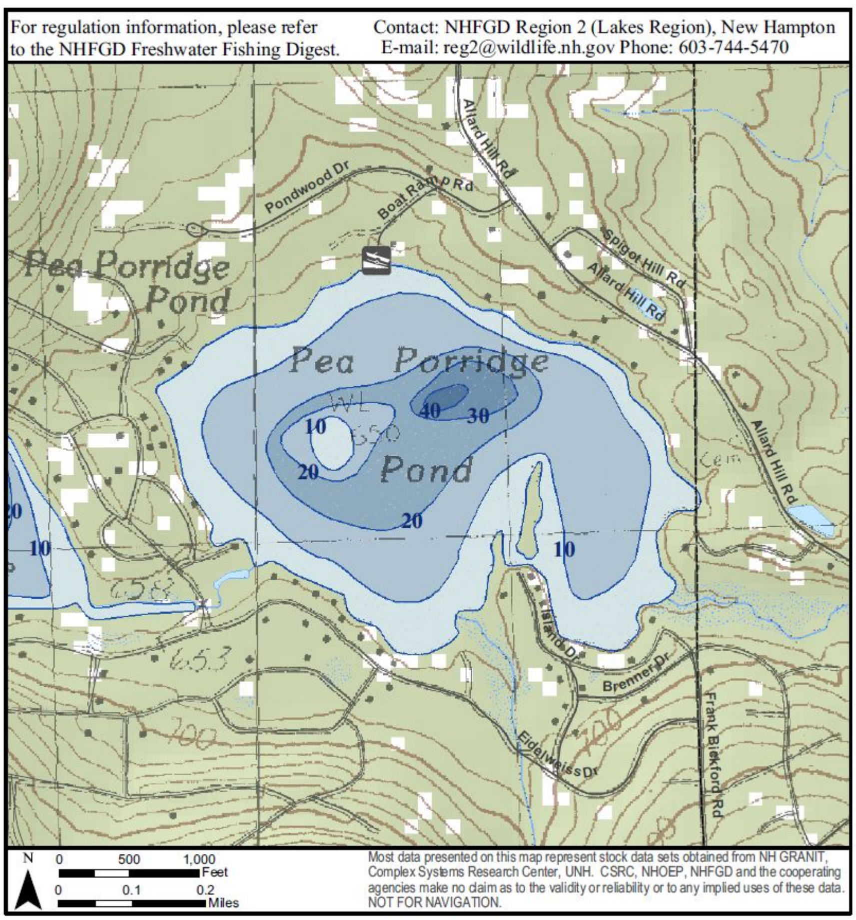

Figure 1. Location and bathymetry of Pea Porridge Pond in East-Central New Hampshire (New Hampshire Fish and Game Department). Sediment core was taken from the deepest part of the lake.

Coring

Two sets of non-overlapping Livingston cores (Wright, 1967) covering 9.57 meters of sediment were taken in two coring expeditions from a water depth of 14.6 m. The first 6.63 meters were cored on March 11, 2008, and the remaining sediment (2.94 meters) was cored on March 17, 2008. Samples were collected every two centimeters and packed into weakly diamagnetic plastic boxes with a volume of 5.3 cm^3. The samples were then stored at 4°C and all measurements were performed on moist samples. Surface sediments were sampled with a Glew corer (Glew et al., 2001) and yielded very soft sediments that were subsampled in 1 cm increments on-site.

Rock-Magnetic Analyses

We used a multi-proxy approach to determine the concentration/abundance of magnetic grains, as well as the mineralogy and the grain-size distribution of those magnetic minerals. Table 1 lists all magnetic parameters used in this study.

Magnetic susceptibility was measured using an AGICO KLY-4 Kappabridge susceptibility meter. Anhysteretic remanent magnetization (ARM) was acquired in a peak alternating field (AF) of 100 mT and a 50 μT bias field using a Magnon International AFD 300 alternating magnetic field demagnetizer. Isothermal remanent magnetization (IRM) was acquired by magnetizing samples three times in a pulsed magnetization field of 100 mT using an ASC-Scientific IM-10-30 pulse magnetizer. Saturation isothermal remanent magnetization (SIRM) was acquired in three field pulses of 1000 mT, and backfield remanence was obtained in pulses of -100 mT and -320 mT by placing the samples in a backwards orientation in the pulse magnetizer. All remanence values were measured using an AGICO JR6 spinner magnetometer with a sensitivity of 2×10^{-6} A/m. Data from these measurements were used to calculate S-ratios and “hard” IRM (HIRM, see Table 1).

Magnetic coercivity distributions were determined for 17 samples through stepwise alternating field (AF) demagnetization of an SIRM, acquired through three pulses of a magnetization field of 1000 mT. The maximum demagnetization field was 305 mT. Hysteresis parameters for 95 samples were measured using a Princeton Measurement Corporations MicroMag 3900 VSM at a peak field of 1.25 T. Hysteresis loops were corrected for para- or diamagnetic contributions.

Table 1 List of Magnetic Measurements Used in this Study

Name	Methodology	Magnetic Interpretation
Mass-normalized susceptibility (χ)	Measured using a KLY-4 Kappabridge susceptibility meter	Reflects the ease of which sediments are magnetized when exposed to a weak magnetic field and depends on the concentration type and grainsize of magnetic minerals present in the sediment.
Anhysteric remanent magnetization (ARM)	Acquired in a peak alternating field (AF) of 100 mT and 50 μT bias field using a Magnon International AFD 300 alternating magnetic field demagnetizer. Units: Am^2/kg	Heavily biased towards small single-domain grains.
Isothermal remanent magnetization (IRM_{100mT})	Acquired by magnetizing samples three times in a pulsed magnetization field of 100 mT using an ASC-Scientific IM-10-30 pulse magnetizer. Units: Am^2/kg	Estimates the presence of all low-coercivity remanence-carrying grains.
Saturation isothermal remanent magnetization ($SIRM_{1000mT}$)	Acquired in three field pulses of 1000 mT using an ASC-Scientific IM-10-30 pulse magnetizer.	Reflects the presence of all remanence-carrying grains.
Backfield IRM IRM_{-100mT} IRM_{-320mT}	Acquired after obtaining SIRM in three field pulses of -100 mT and -320 mT, respectively, using an ASC-Scientific IM-10-30 pulse magnetizer.	Used to calculate S-ratios and HIRM.
S-ratio S_{100mT} S_{320mT}	$S_{x\,mT} = -(IRM_{-x\,mT} / SIRM)$	Correspond to relative changes in magnetic grain size and mineralogy. S-ratios close to 1 indicate the presence of ferrimagnetic particles such as magnetite.
"Hard" IRM $HIRM_{100}$ $HIRM_{320}$	$HIRM_{-x\,mT} = ½ (SIRM + IRM_{-x\,mT})$	Reflects the absolute abundance of medium- and high-coercivity minerals
Magnetic Coercivity Distributions	AF demagnetization curves determined through stepwise alternating field (AF) demagnetization of an SIRM, acquired through three pulses of a magnetization field of 1000 mT, using Magnon.	Reflects the mineralogy of a given sample.
AF demagnetization curves	AFD 300 alternating field demagnetizer	
Hysteresis loops	Measured using a Princeton Measurement Corporations MicroMag 3900 VSM at a peak field of 1.25 T.	Reflects the concentration, grain-size, and mineralogy of a sample.

Results and Discussion

Age Control

Age control for Pea Porridge Pond is based on twelve accelerator mass spectrometry (AMS) ^{14}C dates obtained from bulk organic sediment (see Table 2 for a summary of all ^{14}C dates).

The age of surface sediment was set to modern (-60 yr B.P.). This is justified because the surface core sampled the sediment-water interface and included undisturbed surface sediment. The first ^{14}C sample, obtained from a sediment depth of 2 cm yielded an age of 600 cal. yr B.P. (Table 2). This 'old' age is most likely associated with soil erosion during land clearing. Therefore, a reservoir age of 600 years is assumed for the first date. A reservoir age of 200 years is assumed for the remaining dates.

Sample 2159 yielded a ^{14}C date approximately 2000 years too young. This sample was at the top of thrust 9, which samples the uppermost sediment of the second core and most likely incorporates younger sediment. Therefore, the ^{14}C date for this sample is rejected and not included in any further analyses.

CLAM v. 2.0 (Blaauw, 2010) was used to fit a third order polynomial (IntCal09.14C) calibration curve through the data. The calendar years BP were calculated for all sample depths. The calculations were performed at 95% confidence ranges.

The resulting age-depth curve (Fig. 2) shows no age reversals and no evidence for hiatus. There are no significant or abrupt changes in the sedimentation rate.

Table 2 ^{14}C Dating of Pea Porridge Pond

Sample #	Sample type	Depth (cm)	Lab code	^{14}C age	Error	Assumed reservoir age	cal yrs B.P.
S1	organic sediment	2.5	Beta-317527	660	± 30	600	-5 - -5 (0.3%) 31 – 84 (46.1%) 86 – 138 (25.4%) 223 – 256 (23.1%)
(S1) 1492	organic sediment	32	Beta-312553	1870	± 30	200	1521 – 1629 (85.1 %) 1654 – 1691 (9.8%)
1540	organic sediment	80	Beta-317528	2690	± 30		2753 – 2848 (95%)
1652	organic sediment	192	Beta-317529	4870	± 30		5495 – 5496 (0.4%) 5583 – 5655 (94.5%)
1860	organic sediment	400	Beta-312554	7430	± 40		8180 – 8343 (95%)
1932	organic sediment	472	Beta-317530	8110	± 40		8985 – 9135 (91.7%) 9177 – 9202 (1.8%) 9222 – 9242 (1.5%)
2051	organic sediment	591	Beta-253383	8670	± 60		9532 – 9794 (92%) 9806 – 9816 (0.8%) 9848 – 9865 (1.3%) 9876 – 9886 (0.8%)
2057	organic sediment	597	Beta-266464	8740 (8680)	± 50		9557 – 9900 (95%)
2159	organic sediment	699	Beta-317531	6360 (rejected)	± 40		7177 -7212 (6.4 %) 7244 – 7340 (67.3%) 7348 – 7418 (21.3%)
2195	organic sediment	735	Beta-312555	9360	± 40		10443 – 10451 (1.1%) 10495 – 10695 (93.9%)
2296 (2295)	organic sediment	836	Beta-255716	10410	± 60		12075 – 12440 (85.6%) 12454 – 12529 (9.3%)
2395	organic sediment	935	Beta-244299	12150	± 50		13836 – 14160 (95%)

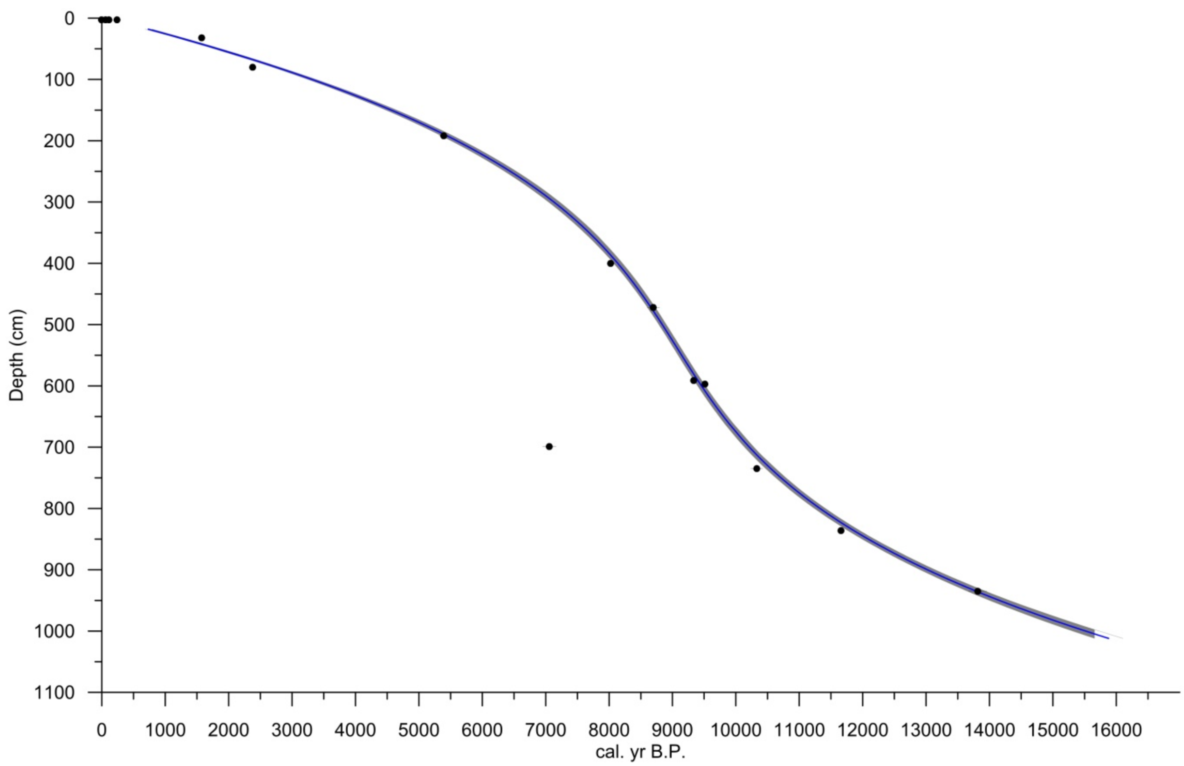

Figure 2. Age-depth curve for Pea Porridge Pond based on ^{14}C measurements. For additional information, see Table 1 and text.

<u>Sediment Magnetic Properties</u>

Figure 3 summarizes the magnetic properties of the core obtained for Pea Porridge Pond. A plot of magnetic susceptibility vs IRM shows a linear relationship; therefore, IRM is not shown (Fig. 3). The sedimentary record is divided into six zones based upon distinct, observed changes in the magnetic properties:

Zone 1 (prior to 14 ka) is characterized by a low concentration of organic matter in the samples (LOI= 0%). High χ, ARM, and IRM (not shown), support these data, indicating a high concentration of magnetic minerals (Figure 3 b, c). The ARM-ratio (Figure 3d) is low, suggesting that magnetic minerals are coarse-grained (multi-domain, MD <10 μm). In a plot of magnetization (M_r/M_s) vs the coercivity ratio (Hcr/Hc) (Day et al., 1977), the samples plot along a range of grainsizes from coarse pseudo-single domain (PSD; 1-10 μm) to multi-domain (MD) grains (Fig. 4). S-ratios (Figure 3e) are fairly close to 1, and indicate a high abundance of low-coercivity ferrimagnetic minerals (e.g. magnetite). However, HIRM is high as well (Figure 3f) and suggests the presence of high-coercivity minerals. Coercivity distributions (Figure 3h) show samples to be completely demagnetized in a 300 mT alternating magnetic field, with a mean destructive field of 25 mT, again, suggesting the dominance of a low-coercivity ferrimagnetic component. Therefore, although there appears to be high-coercivity minerals present, they seem to be overpowered by low-coercivity minerals. χ_{hf} is highest in this zone (~ 88.38, Figure 3i) and indicates that the samples are mostly paramagnetic clays.

Zone 2 (14.0-13.6 ka) is likely a transitional period and displays a slight increase in LOI (Figure 3a), suggesting an increase in the relative concentration of organic matter. The zone displays lower values for χ, ARM, and IRM (not shown) (Figure 3 b, c), which indicates a decrease in the concentration of magnetic minerals present. The ARM-ratio is still low (Figure 3d), which suggests that the magnetic minerals are still coarse-grained even as there is a decline in the input of ferrimagnetic minerals. In the Day plot (Figure 4), samples plot within the PSD and MD ranges, and show that the samples are still a mix of coarse-grained PSD and MD. S-ratios close to 1 (Figure 3e) indicate that samples from this zone are still dominated by low-coercivity ferromagnetic minerals. HIRM drops (Figure 3f), corresponding with S-ratios suggesting the presence of low-coercivity minerals. Coercivity distributions from this zone show little change from those in Zone 1 (Figure 3h), and still suggest the presence of a dominant low-coercivity component or a relative increase of diamagnetic matter. χ_{hf} also drops slightly (Figure 3i), indicating the presence of fewer paramagnetic minerals.

Zone 3 (13.6 -10.0 ka) exhibits an increase in the concentration of organic matter (LOI increases to 20 percent, Figure 3a). This is consistent with low χ (Figure 3b) and IRM (not shown), which reflect even lower concentrations of ferrimagnetic minerals. Increases in ARM (Figure 3c) suggest the presence of single domain grains, and increases in the ARM-ratio (Figure 3d) denote an increase in the relative abundance of fine single-domain (SD) grains (~0.025 – 0.1 μm). In Figure 4, samples plot along a mixing line between 2.5 and 0.2. (Dunlop, 2002). S-ratios ~ 1 (Figure 3e) and low HIRM values suggest that the magnetic component is dominated by low-coercivity minerals. Coercivity distributions show a distinct coercivity component (MDF = 35-50 mT, Dp = 0.2) (Figure 3h) in this zone, which suggests the presence of a biogenic soft (BS) component indicating biogenic magnetite (Egli, 2004). χ_{hf} further decreases (Figure 3i) in this zone.

Zone 4 (10.0-8.5 ka) represents a transitional period. In this zone, LOI stays consistent at about 20 percent (Figure 3a) and χ, ARM, and IRM (not shown) are very low (Figure 3b, c). The ARM-ratio is initially low, indicating coarse-grained (PSD to MD) minerals, but increases towards the top of the zone (Figure 3d). The ARM-ratio is "noisy" due to the low absolute values of ARM and IRM. S-ratios decreasing from 1 to 0.4 (S_{100}) and 0.75 (S_{320}) (Fig. 3e) reflect a relative increase in the abundance of high-coercivity minerals, even as their absolute concentrations decrease (low HIRM, Fig. 3f).

Zone 5 (8.5-3.0 ka) demonstrates a slight increase in LOI (Fig. 3a), suggesting a possible addition of more organic material. Low values for χ, ARM, and IRM (not shown) (Fig 3b, c) show that the concentration of magnetic minerals in the samples is low. A high ARM/IRM ratio (Fig. 3d) suggests the presence of single-domain particles. S-ratios remain relatively constant at 0.4 and 0.75, respectively (Figure 3e) and HIRM also remains low (Fig. 3f). Coercivity distributions from this zone show a component that cannot be completely demagnetized in a 300 mT AF (Fig. 3h). κ_{hf} is less than zero (Fig. 3i), indicating diamagnetic organic matter, and a Day plot confirms the samples to be almost entirely diamagnetic, and generally finer (Fig. 4).

Zone 6 (<3.0 ka) displays the highest values of LOI (30-50 %, Fig. 3a). There is a slight increase in χ, ARM, and IRM (not shown) (Fig. 3b, c) and the ARM/IRM ratio also increases (Fig. 3d), perhaps indicating the presence of single-domain grains. S-ratios also increase (Fig. 3e).

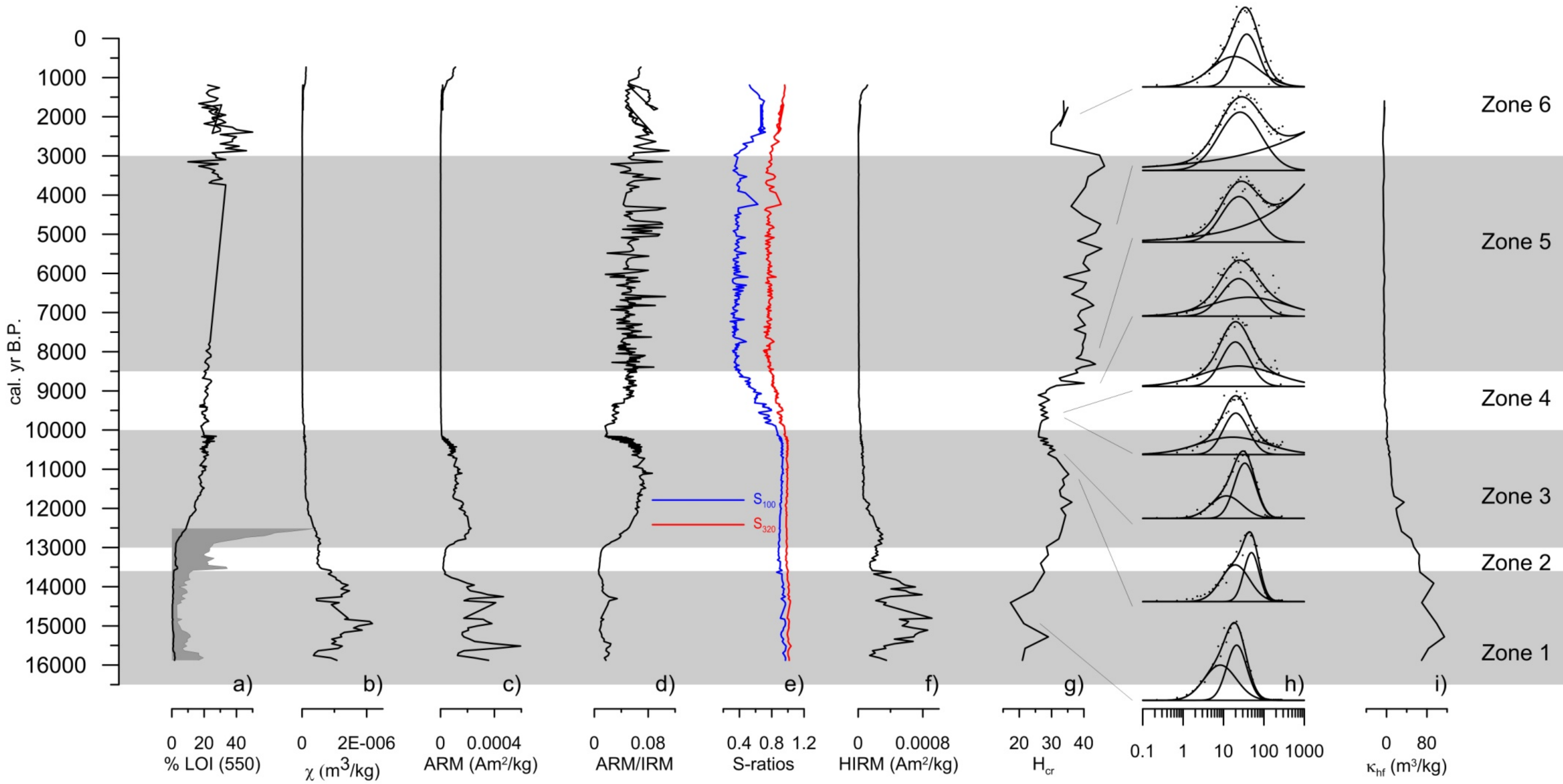

Figure 3. Magnetic properties of Pea Porridge Pond as a function of sediment age. (a) Loss-on-ignition reflects the presence of organic matter in a given sample. The gray curve is the LOI curve expanded by a factor of 10 and shows the first sharp increase in LOI.(b) Magnetic susceptibility (χ) provides a rough estimate of the abundance of magnetic minerals in a given sample. (c) Anhysteric remanent magnetization (ARM) is heavily biased towards small single-domain grains. (d) The ARM/IRM ratio can be used as a proxy to determine the relative abundance of fine, single-domain grains.
(e) S-ratios reflect the ratio of magnetite to hematite. Higher S-ratios generally suggest the presence of more magnetite in a sample. Lower S-ratios are likely due to the presence of hematite.
(f) “Hard” isothermal remanent magnetization (HIRM) is a measure of the concentration of medium- and high-coercivity minerals. (g) Coercivity of remanence (Hcr) corresponds to the ease of demagnetizing a given sample. (h) Coercivity distributions of IRM reflect the mineralogy of a given sample. (i) High-field susceptibility(κ_{hf}) reflects the presence of magnetic minerals. κ_{hf} <0 commonly indicates diamagnetic organic matter.

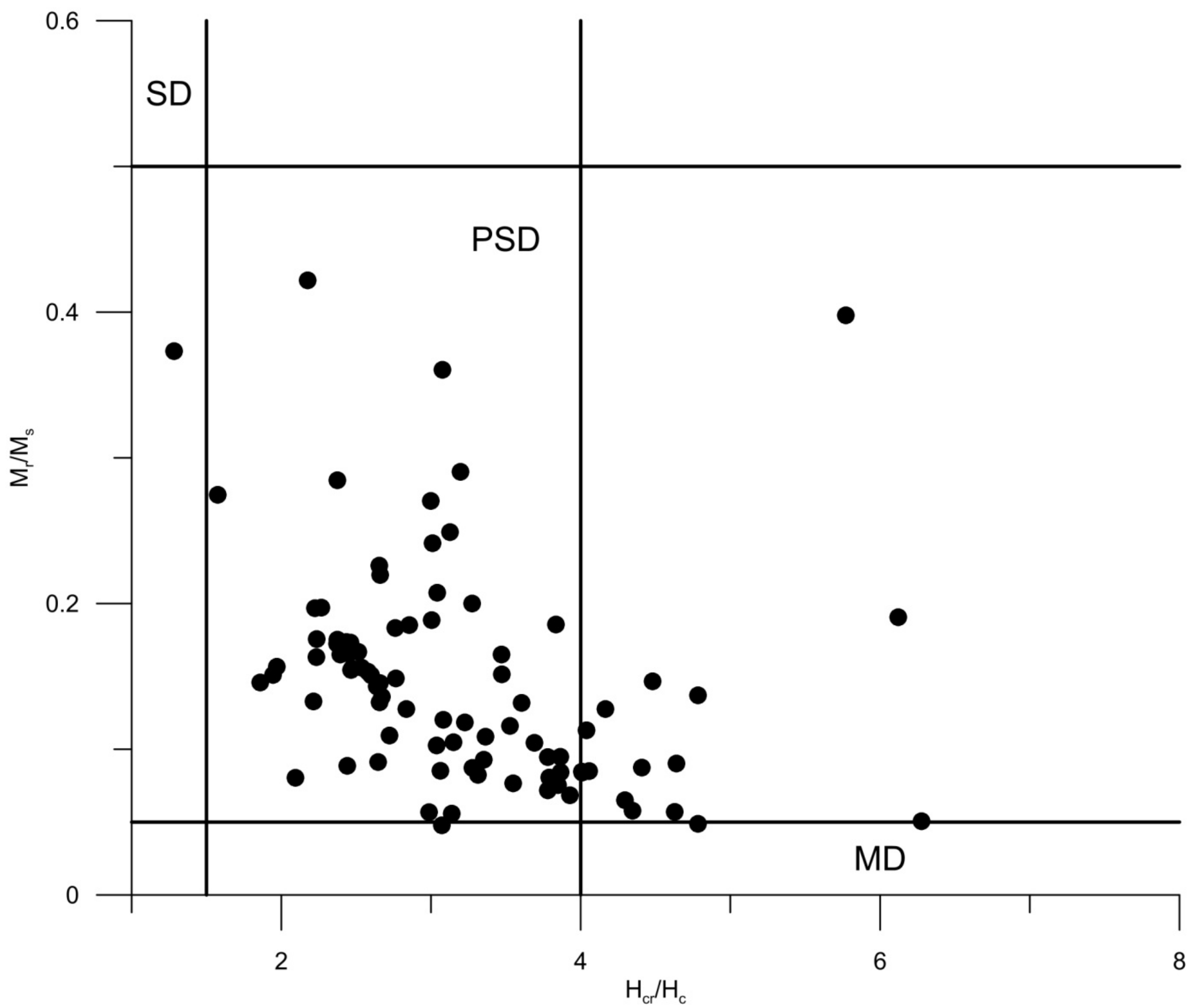

Figure 4. A plot of remanent saturation magnetization (M_r) to saturation magnetization (M_s) against the ratio of remanent coercivity (H_{cr}) to coercivity (H_c) (Day et al., 1977). Provides an estimate of the magnetic grain size.

Magnetic Properties and the Lacustrine Environment

Changes in the magnetic properties of Pea Porridge Pond suggest that the processes of erosion, dilution, and dissolution likely affect the concentration, grain-size, and mineralogy of the Fe-minerals present. Zone 3 is also likely affected by authigenic minerals produced by magnetotactic bacteria. Zones 4 and 5 exhibit very little change in sediment or organic input. Magnetic data from Zone 6 indicates an increase in the input of magnetic sediments and is most likely due to the effects of soil erosion resulting from changes in lake levels or anthropogenic activity (Geiss et al., 2003).

Sediments deposited *prior to 14.0 ka BP (Zone 1)* are dominated by clastic sedimentary input (low LOI-values), which results in high concentrations of both low- and high-coercivity minerals (high values of χ and HIRM). These detrital minerals are coarse-grained (PSD to MD - ARM/IRM ~ 0.02 - 0.04 μm) and the overall sediment magnetic properties are dominated by low-coercivity minerals (S-ratios ~ 1) due to the high saturation magnetization of ferromagnetic minerals such as (titano) magnetite or maghemite (Hunt et al., 1995). Contribution of these minerals is likely due to erosion of the basin slopes.

Zone 2 (14.0-13.6 ka) is a transitional zone characterized by a higher concentration of organic matter concentration and an overall lower abundance of magnetic minerals (LOI increases, χ, ARM, IRM, and HIRM all decrease). This suggests decreased erosion resulting from further stabilization of the landscape as well as an increase in the general productivity of the lake. Sediments from this zone are still coarse-grained (PSD to MD) and dominated by a low-coercivity component (S-ratios ~ 1).

Sediments deposited during *Zone 3 and younger (13.6 -10.0 ka)* are likely to be affected by the processes of dilution and dissolution. Dilution of clastic sediments by the input of weakly magnetic or non-magnetic sediments can be caused by changes in lake productivity or inputs of clastic material (Geiss et al., 2003). Low values of χ and IRM (not shown) support this interpretation.

The addition of organic matter can dilute the mineral fraction of the sediment, but it is much more likely that the observed decrease in the concentration of magnetic minerals is due to dissolution (Williams et al., 1996). LOI rises by approximately 20%, so dilution of a magnetic detrital component by organic matter can account for only a 20 percent drop in concentration parameters (χ, IRM, and ARM). Concentration-dependent parameters, however, drop by approximately 95 percent, indicating that magnetic minerals are affected by both dilution and dissolution processes.

The decomposition of organic matter consumes oxygen and creates an environment in which Fe-oxides are reduced and dissolved. This results in a decrease in the concentration of magnetic minerals (Williams et al., 1996).

Zone 3 is also likely to be influenced by the production of authigenic material by magnetotactic bacteria (narrow coercivity distributions, increase in ARM, ARM/IRM) (Egli, 2004), which is superimposed on the overall long-term dissolution trend.

Zone 4 (10.0-8.5 ka) appears to be a transitional period. Input of clastic materials is low (low values of χ, IRM, and ARM) and the input of organic material remains constant (LOI remains the same). The overall sediment magnetic properties are dominated by higher-coercivity minerals (S-ratio decreases).

Zone 5 (8.5- 3.0 ka) shows little change in sedimentary input (low χ, IRM, ARM, HIRM) but the overall sediment magnetic properties confirm the presence of high-coercivity minerals (low S-ratios, high H_{cr}) and samples are almost entirely diamagnetic ($\kappa_{hf} <0$).

Sediments deposited *after 3.0 ka B.P. (Zone 6)* indicate a slight increase in the input of clastic sediments (lower LOI values) and results in higher concentrations of low-coercivity minerals (higher values of χ, IRM, ARM; S-ratios ~1). This increase in clastic input is likely caused by erosion due to either higher lake levels or anthropogenic activities (Geiss et al., 2003; Shuman et al., 2004).

Magnetic Properties and Paleoclimatic Change

Zone 1: Cold, artic conditions

The White Mountains in New Hampshire deglaciated between 14.0 and 13.6 ka B.P. (Davis et al., 1984). The high values of magnetic susceptibility, ARM, IRM, HIRM, and high-field susceptibility prior to 14.0 ka (Zone 1) are indicative of an unstable landscape in which erosion contributed to the high concentration of magnetic minerals. The initially high rate of sedimentation (31.37 yr/cm) continually decreases (to 23.79 yr/cm) suggesting an environment in which erosion was the main source of magnetic minerals until the landscape stabilized under a more or less continuous plant cover. The decrease in the sedimentation rate is most likely not due to increases in plant cover, as the concentration of organic matter does not increase during this zone.

Zone 2: Cold conditions

The transitional Zone 2 (14.0-13.6 ka) is characterized by an increase in the relative concentration of organic matter and a decrease in the concentration of magnetic minerals. The sedimentation rate continues to decrease (23.79-19.17 yr/cm), indicating further decreasing erosion rates. This is suggestive of a stabilizing landscape and increases in the general productivity of the lake. As warming increases productivity in the lake, organic matter decomposition results in anoxic sediment conditions, and the dissolution of Fe-oxides occurs, decreasing concentration-dependent parameters such as magnetic susceptibility, ARM, IRM, and HIRM. Both increases in productivity and the preservation of some of the organic matter in the lake result in a higher percentage of LOI.

Zone 3: Cold (until ~12.2 ka) to cool, driest conditions

Spruce is generally considered to be one of the first tree species to invade New England (Davis et al., 1984). Zone 3 (13.6 -10.0 ka) covers the time during which the spruce maximum occurred (~11.0 ka). Most Fe present in soils is insoluble, however, terrestrial plants have evolved mechanisms to enhance the dissolution of Fe in soil. This is commonly achieved through root excretions of organic acids such as citrate (Jones et al., 1996). The expanse of spruce near Pea Porridge Pond may have caused both acidification of the soil and enhanced Fe-dissolution in the soil and groundwater. Dissolution of Fe in the groundwater may account for the low concentration-dependent parameters observed. The supply of Fe-rich groundwater to the lake enabled production of biogenic magnetite (high ARM, high ARM/IRM). A similar magnetic response to a change from deciduous to coniferous forest has been observed for Steel Lake in northern Minnesota (Geiss et al., 2003).

Zone 4: Cool, driest conditions

Zone 4 (10.0-8.5 ka) is characterized by a gradual warming trend. During Zone 4 (10.0-8.5 ka), sedimentation rate decreases even further (9.5-7.83 yr/cm), organic matter concentration remains 20 percent, and magnetic susceptibility, ARM, IRM, and HIRM are all very low. High-field susceptibility shows a transition from paramagnetic clays to diamagnetic organic matter.

Zone 5: Warm, wet (until ~6.5 ka) to warm, dry conditions

Zone 5 (8.5- 3.0 ka) does not appear to change significantly from Zone 4, and concentration-dependent parameters remain low. However, it is during this zone that the sedimentation rate appears to increase (7.83-29.53 yr/cm). Though the rate of sedimentation appears to increase significantly, it must be kept in mind that Zone 5 comprises the largest time period (8.5-3.0 ka) and so this increase does not happen quickly. The increased sedimentation does suggest a change in land cover, and an increase in erosion. This may be due to the land uses of early human civilizations.

Zone 6: Cool, wettest conditions

The final zone 6 (<3.0 ka) is characterized by a further increase in the sedimentation rate (up to 35.83 yr/cm) most likely due to an increase in erosion as anthropogenic activities led to the clearing of the forest surrounding Pea Porridge Pond. Whereas in earlier zones, human development was minimal or non-existent, it is in this zone that human activity increases. Magnetic susceptibility, ARM, IRM, and HIRM slightly increase, and high-field susceptibility shows a trend towards less diamagnetic material and perhaps a return to paramagnetic minerals. This increase in the concentration of magnetic minerals may indicate a return to a cooler climate.

Overall, the magnetic properties of sediment from Pea Porridge Pond suggest a gradual warming trend up until 3.0 ka (Zone 5). As the climate warms, there is less input of clastic materials as erosion decreases, and an increase in the concentration of organic matter as warmer conditions allow for increased productivity in the lake and increased plant cover on the slopes surrounding the lake. It is only recently that the climate appears to get cooler.

The climatic changes inferred from magnetic zones 1-6 in Pea Porridge Pond appear to agree with an earlier study of moisture-balance change in Echo Lake, New Hampshire (Shuman et al., 2004) linking changes in the sediment accumulation rate with changes in moisture availability and lake levels. Shuman et al. (2004) suggests four periods of moisture change. During 11.0 – 8.0 ka, a low sediment accumulation rate indicates that conditions unfavorable for erosion and surface runoff existed (i.e. low lake levels, dry climate) (Shuman et al., 2004). An increase in sediment accumulation by 8.0 ka, however, suggests an increase in moisture and higher lake levels (Shuman et al., 2004).. A return to dry conditions is assumed for 5.0 – 2.0 ka as sediment accumulation decreases, but the past 3200 years suggests a wetter climate as sediment accumulation increases (Shuman et al., 2004).

Sediment accumulation rates for Pea Porridge Pond seem to follow this pattern. In Zone 1 (prior to 14.0 ka) erosion contributes to an initial sediment accumulation rate of 31.37 yr/cm that decreases throughout the zone. In Zone 2 (14.0–13.6 ka), the sediment accumulation rate decreases further, suggesting a climate drier than in Zone 1, and the sediment accumulation rate of Zone 3 (13.6 - 10.0 ka) decreases even further. This decrease continues throughout Zone 4 (10.5-8.5 ka) until Zone 5 (8.5-3.0 ka). Zone 5 is characterized by an increase in sediment accumulation, suggesting that the climate has shifted from dry to moist conditions. Sediment accumulation continues to increase in Zone 6 (<3.0 ka) and indicates the wettest climate thus far.

Conclusions

The sediment magnetic record from Pea Porridge Pond reflects regional climate change in New Hampshire throughout the Holocene. Changes in the concentration, mineralogy, and grain-size distribution of magnetic minerals reflect changes in the lacustrine environment, which can then be used to reconstruct climatic conditions.

Colder, drier zones correspond to sediment with high concentrations of magnetic minerals (i.e. hematite and magnetite), and contain high relative amounts of magnetite to hematite. The sediment accumulation rate for drier zones is generally low. Warmer, moister zones correspond to sediments with low concentrations of magnetic minerals, and have relatively higher amounts of hematite than magnetite. Warmer zones also show a shift from paramagnetic to diamagnetic, organic matter. The sediment accumulation rate for moist zones is higher as rises in lake levels contribute to erosion of the basin slopes. Comparisons with other climate proxies such as pollen are necessary, and will help to clearly determine the effects of climate on the sediment record.

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